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Cogenerating electricity from charcoaling: A promising new advanced technology ☆

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ABSTRACT

This article presents a technical review of the status of the charcoal cogeneration technologies. Cogeneration of electricity from charcoal production is an emerging technology, with promising worldwide application. When charcoal is produced through traditional slow pyrolysis batch cycle processes, about 50% of the original firewood energy is lost through the pyrolysis gases. These gases are made of condensable and non-condensable portions. The condensable fraction consists of an energy-rich mix of compounds that can be extracted through condensation. The non-condensable fractions consist of flammable gases such as CO, H_2 and CH_4, which can used to produce heat and power, either using steam cycle systems, or other technologies such as Stirling engines or even ECGT (External Combustion Gas Turbines). Several companies in Brazil, France, Denmark and Australia are currently pursuing the development of charcoal cogeneration. To overcome the usual instability in the availability of energy from pyrolysis gases when charcoaling in batch cycles, most companies are developing charcoal production units that cluster several charcoal kilns together, operating them in a staggered sequence, in order to stabilize the energy output from the system. Furthermore the usage of complementary fuels such as biomass residues or other petroleum fuels is investigated, to help stabilize cogeneration and increase power output. As this technology develops, it could offer several benefits including entrepreneurial opportunities, livelihood diversification and increased incomes in rural areas for charcoal entrepreneurs, as well as reduction of greenhouse gases emissions and additional renewable energy capacity. Sub-Saharan Africa, the leading charcoal production region in the world, suffers acute deficits in electricity access, and could benefit from this technology. However to enable such technology to flourish in the future, an appropriate legal framework and business model should be specifically developed for each country.

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Introduction

Charcoaling, or slow pyrolysis is the process of thermochemical decomposition of wood at elevated temperatures (around 450 °C) in an oxygen-starved environment, in order to produce lump charcoal from wood. In the traditional batch process, pyrolysis can take a week or more to complete. This process has been well-known since the early Bronze Age (about 3500 B. C.), when people first used it to achieve the temperatures necessary to make an alloy of copper and tin (Harris, 1999).

Dry wood has calorific value between 19 and 20 MJ/kg. It consists of roughly 70% volatile matter 28% fixed carbon and 2% ash (Ayhan, 1997). During charcoaling, wood is heated in the absence of air, which drives off most of the volatile compounds and leaves behind primarily fixed carbon. Charcoal, the resulting product, has a calorific value of ~30 MJ per kg and consists of just 15–20% volatile matter (Antal et al., 1996).

In normal conditions, considering air dry wood with 20% of humidity, about 30% of the original firewood mass ends up as charcoal, and 70% as pyrolysis gases. These gases, which are commonly released into the atmosphere, contain nearly 50% of the original energy embodied in the woody feedstock (Halouani and Farhat, 2003).

Fig. 1 demonstrates this energy loss, by showing the energy balance for charcoal production in the Brazilian state of Minas Gerais. The state, which hosts the largest production of charcoal for industrial usage in the world (see Bailis et al., 2013-this issue), reports the energy losses in the production of charcoal of roughly 50% of the overall energy input.

The pyrolysis gases consist of condensable and non-condensable fractions. The condensable fraction contains methanol (CH_3OH), acetic acid (CH_3COOH), water vapor (H_2O), and tars (Brito, 1990). Historically, wood tar has been the most readily captured component. Tar was commonly used to seal the hulls of wooden ships and roof tiles by the ancient Greeks. It was also the main Swedish export between the 14th and 18th centuries, before metal ships became more common (Kaye, 1997). Tar has also other important uses such as

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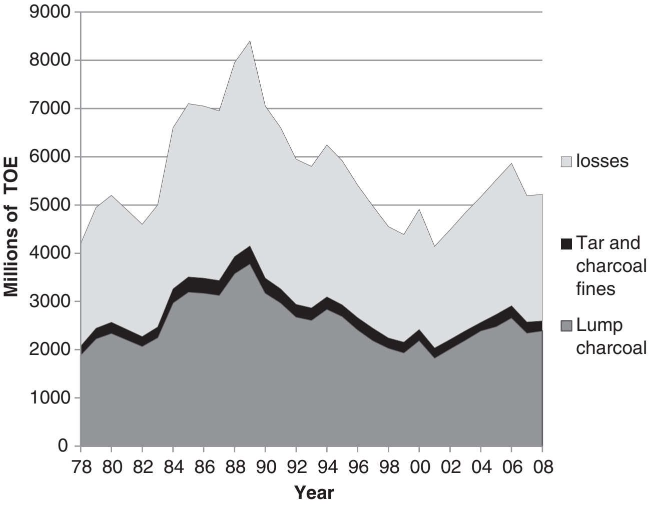

Fig. 1. Total energy breakdown from charcoal production in Minas Gerais, Brazil from 1978 to 2008, as lump charcoal, other sub-products (charcoal fines and tar), and losses (smoke). (Source: BEEMG, 2009).

microbicide, wood flavoring, wood preservative, and asphalt laying (Kaye, 1997). Other condensable components like methanol and acetic acid, although useful, are not often captured from charcoaling because they can be produced more cheaply from fossil fuels.

The other portion from pyrolysis smoke is non-condensable gases, which include gases such as CO_2, CO, H_2, CH_4, and other light hydrocarbons, as well as particulate matter and more complex compounds like polycyclic aromatic hydrocarbons (PAH). The exact combination of compounds present in the mixture depends on the original feedstock as well as the temperature and rate of pyrolysis. The resulting mixture is flammable with a calorific value between 5 and 15 MJ/kg (Raveendran and Ganesh, 1996).

In traditional charcoal production, common in parts of sub-Saharan Africa, Latin America and Asia, pyrolysis gases are vented to the atmosphere. In more advanced production systems, the non-condensable gases may be flared to reduce the products of incomplete combustion. Less often, they may be burned to generate heat for pre-drying the firewood and/or initiating pyrolysis, which improves the efficiency of the process.

Recently, as concerns about energy security and climate change have become more apparent, industrial charcoal producers have begun exploring the cogeneration as a way of utilizing the energy embodied in pyrolysis gases. Several developments for this technology are underway throughout the world. In the following sections, we examine the potential of this new application for and consider its application in leading charcoal production areas around the developing world.

Technological approaches for cogeneration

Traditional pyrolysis

To make charcoal via slow pyrolysis[1] different technological approaches can be used. In developing regions, charcoal is most commonly produced from trees harvested from native woodlands and pyrolysis is carried out either in a pit kiln, in which a hole is dug on the ground, filled with firewood and covered with earth and leaves, or an earth-mound kiln, in which firewood is stacked on the ground and covered with earth and leaves. These technologies have an advantage in developing country settings because they require no outside materials and can be constructed in any location where wood is available. In both cases the firewood load is left to burn for several days in an oxygen-starved environment. Reports of yields on a mass basis (mass of charcoal output ÷ mass of dry wood input) vary from less than 10% to as much as 30% (Bailis, 2009). These kilns must be closely monitored by the charcoal producer to ensure that cracks do not develop and allow air to enter, as this would shift some portion of the charge from pyrolysis to combustion, and reduce yields. Attempts have been made to “modernize” these methods by adding air-control mechanisms like chimneys (e.g. the Casamance kilns introduced in West Africa in the 1980s). This improves conversion efficiency and allows some portion of the condensable gases to be extracted (FAO, 1983). However, given the rudimentary construction and itinerant nature of the kilns, none of these approaches are suitable for cogeneration.

Other traditional methods of charcoal production such as brick kilns are common in countries like Brazil, where the industry is more reliant on silvicultural management than on harvesting trees from native woodlands. These are small permanent brick structures in which firewood is loaded. As with earth- and pit-kilns, the wood load is left to burn for several days and must be closely monitored to ensure air does not enter the pyrolysis zone. Yields from brick kilns are typically around 30% (Bailis, 2009). Brick kilns could, in theory, be adapted to a cogeneration system. There is more control over airflow, the kilns are long-lived, and offer the ability to capture the smoke. We explore this option in Smoke flaring section below.

Advanced pyrolysis

Increasingly sophisticated pyrolysis technologies are also being explored. These include

- Micro-wave kilns, in which wood is loaded in a conveyor that passed through microwave magnetrons. Pyrolysis occurs in a relatively quick continuous process, with charcoal emerging on the far side of the conveyor after a few hours (Miura et al., 2004).
- Container kilns in which a movable metal container (reactor) is loaded with wood and moved between different places for each stage of the pyrolysis process (e.g. drying, pyrolysis, and cooling). This also obtains charcoal in few hours.
- Continuous kilns in which charcoal is made in a continuous process. Here, the wood is loaded on the top of a tall kiln and descends within the kiln, going through the phases of drying, torrefaction, and pyrolysis. Charcoal is obtained at the bottom. Co-products like tar, methanol, acetic acid and non-condensable gases are also continuously extracted (FAO, 1985).

During slow pyrolysis roughly 70% of the mass and 50% of the energy embodied in the woody feedstock escapes in the form of pyrolysis gases. These advanced technologies allow this energy to be captured and utilized in various ways, including cogeneration.

Tar condensation

The easiest way is to condense the tar with simple system that passes channels hot pyrolysis gases through cool air. This has been done for centuries. More advanced systems using liquid cooling and cyclones can also be used. Tar is dense bio-oil with a calorific value of between 20 and 25 MJ per kg (Raveendran and Ganesh, 1996). It can be used as a boiler fuel to substitute for heavy fuel oil, although it represents less than 10% of the original firewood mass (Rima, 2008).

During the energy crises of the 1970s and 80s, there were several attempts by Brazilian charcoal producers to condense the tar as a source of bio-oil. Some examples of tar as a fuel for power generation persisted until more recently. For example, the Barreiro power plant in the southeastern city of Belo Horizonte, in which from 2003 to

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[1] We use the term slow pyrolysis here to differentiate this process for making charcoal from fast pyrolysis, an emerging process to maximize bio-oil output with minimal production of solid char (Bridgwater, 2012).

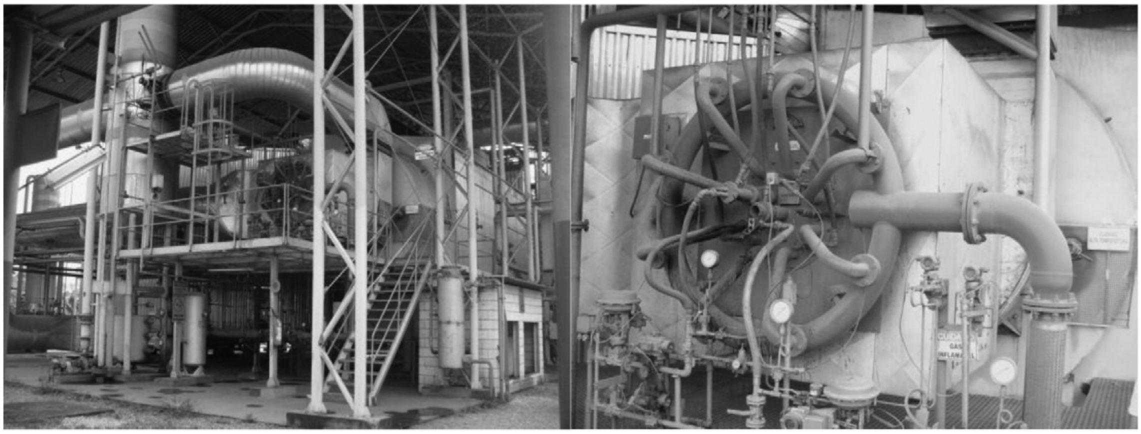

Fig. 2. View of the Barreiro power plant boiler (left photo) and detail view of the fuel feeding system in the boiler (right photo), with the central hole (open tube) used for wood tar injection, and the main round tube used for steel furnace gas injection.

2009 the Minas Gerais state power utility (CEMIG)[2] operated a 15 MW power plant designed to use tar as complementary fuel to hot exhaust gases from steel furnaces (Fig. 2). The plant used tar at the rate of 500 kg per hour. It required a tar filter and a heater to reduce the viscosity of the tar before it was injected under pressure inside the boiler. However after 2009 CEMIG stopped using tar because the supplier found a more lucrative market (Miranda, 2012).

Smoke flaring

Some other technologies attempt to capture the both condensable and non-condensable fractions of pyrolysis gas. For that, special installations need to be set up, in order to channel the pyrolysis gases from the kiln to a combustion chamber. One challenge arises with batch systems, because the constitution of pyrolysis gases varies over time. In a given batch, the flow of gases initially contains a high fraction of water vapor evaporated from the wood, which results in a gaseous mixture with relatively low calorific value. As pyrolysis progresses, the temperature rises and water content diminishes, producing a gas with higher calorific value (Table 1). For a given batch, gas with high calorific value is produced for about 30% of the total charcoaling period (including cooling period) (Miranda, 2012). This cyclical variation in calorific value of pyrolysis gases presents problems for cogeneration, due to the instability in the availability of energy.

As previously explained, the quality of the pyrolysis gas changes within each cycle of pyrolysis (batch), going from an initial low-energy phase due to high water content, to a later phase with an energy-rich gas. The problem is compounded because after the pyrolysis cycle is complete, the charcoal needs to be cooled and unloaded, then the kiln must be reloaded with fresh wood and reignited.

Several measures can be introduced to overcome these limitations. First, it is possible to reduce the amount of water in the firewood by using the residual heat generated during the flaring of the gases to pre-dry the firewood. In one model, pre-drying is facilitated by the use of mobile metal container-kilns (Fig. 3). These have been introduced in firms operating in Brazil and France.[3] The container is loaded with air-dried wood and placed in a location where hot air from the combustion of pyrolysis gases is forced through it. This reduces the moisture content of the wood by 80%, to about 5–8% humidity content. Next, the container filled with dried wood is moved and placed in a location for pyrolysis. Pre-drying is also possible with permanent brick kilns, but requires constructing a separate chamber (kiln) for drying the firewood using flared pyrolysis gas, and then transferring the dried wood to the brick kiln for pyrolysis. Some companies active in Brazil are working to further develop this method.

Although pre-drying removes much of the wood moisture, the calorific value of the pyrolysis gas still varies over time. A second measure that can be used to smooth the variation in calorific value over time involves a system of multiple kilns (12 or more) operated in a staggered sequence. As more kilns are added, the calorific value of gases entering the cogeneration unit is more stable and capable of sustaining stable power cogeneration (Fig. 4).

Nevertheless there could be still moments where the quality of the gas decreases to a point that would be insufficient to sustain full cogeneration. Situations like breakdown of any kiln, or excess humidity on firewood load, or even delay to run any of the kilns, could jeopardize cogeneration. In these cases, other gaseous fuels like biogas, natural gas or LPG could be held in reserve and fed into the cogeneration system.

It is also possible to design the cogeneration system to utilize a solid fuel in order to increase cogeneration capacity and ensure that lapses in quality or supply of pyrolysis gas do not affect plant operations. Some Brazilian charcoal producers, who manage their own tree plantations, are considering using logging wastes such as branches, leaves and tops as a supplemental source of fuel (see Miranda, 2012; Bailis et al., 2013-this issue).

Table 1
Characteristic temperatures, carbonization and gas content in each phase of wood pyrolysis.

Parameters	Drying	Pre-carbonization	Beginning of tars phase	Tars phase
Process temperature (°C)	150–200	200–280	280–380	380–500
Carbon content of charcoal (%)[a]	60	68	78	84
NCG (%)[b]				
CO_2	68	66.5	35.5	31.5
CO	30	30	20.5	12.3
H_2	–	0.2	6.5	7.5
Hydrocarbons (mainly CH_4)	2	3.3	37.5	48.7
NCG heat value (kcal/Nm^3)[c]	1100	1210	3920	4780

[a] (%) percentage based on dry mass of charcoal.
[b] (%) percentage based on dry mass of non-condensable gases (NCG).
[c] Based on NCG mass balance (Brito and Barrichelo, 1981).

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[2] CEMIG has a total installed capacity of nearly 7000 MW.

[3] For example, Rima Industrial and Carbonex are both developing metal container kilns that utilize heat from pyrolysis to pre-dry wood (Miranda, 2012).

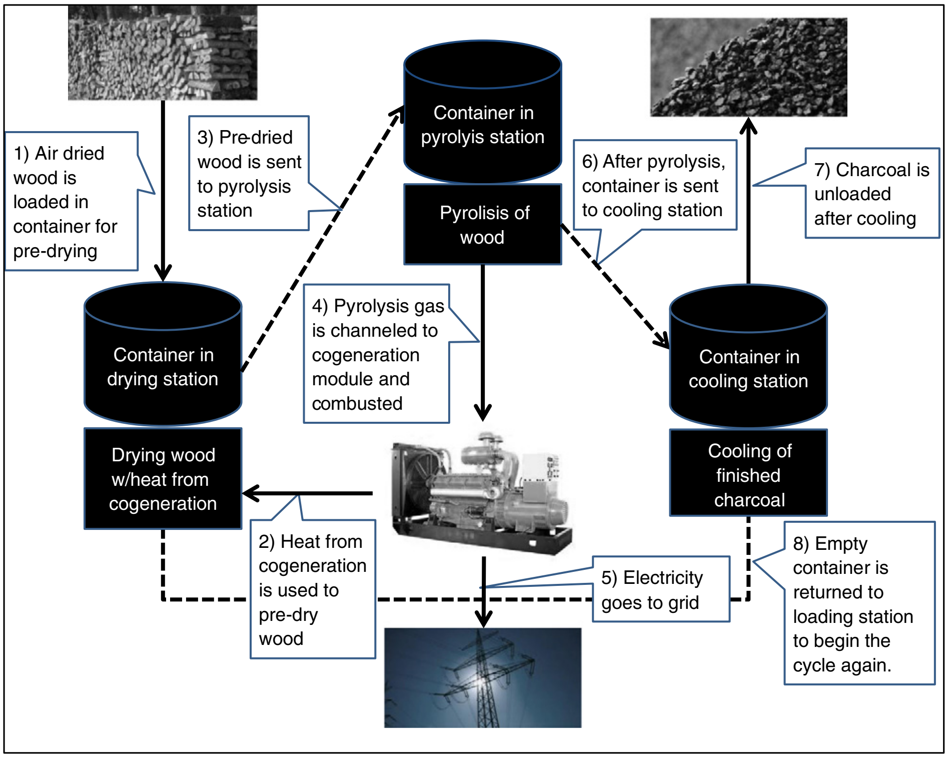
1) Air dried wood is loaded in container for pre-drying
3) Pre-dried wood is sent to pyrolysis station
Container in pyrolyis station
Pyrolisis of wood
6) After pyrolysis, container is sent to cooling station
7) Charcoal is unloaded after cooling
Container in drying station
4) Pyrolysis gas is channeled to cogeneration module and combusted
Container in cooling station
Drying wood w/heat from cogeneration
Cooling of finished charcoal
2) Heat from cogeneration is used to pre-dry wood
5) Electricity goes to grid
8) Empty container is returned to loading station to begin the cycle again.

Fig. 3. An example of a charcoal cogeneration cycle utilizing waste heat for pre-drying.

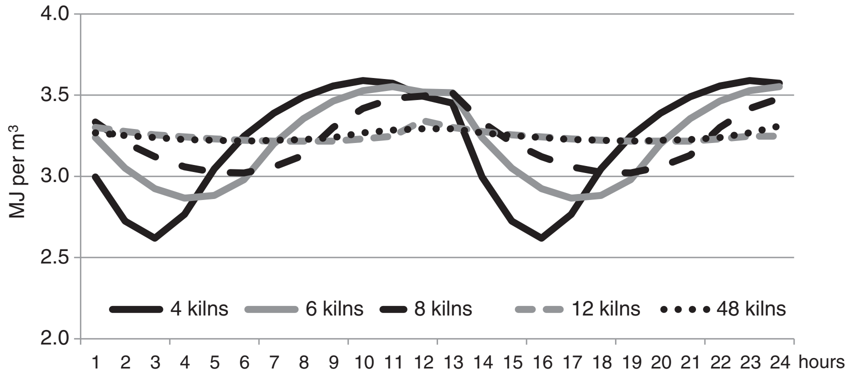

Fig. 4. Variation in calorific value of pyrolysis gas with variation of number of kilns in series (Vilela, 2010).

Perspectives for cogeneration technology

The development of charcoal cogeneration technology opens up new horizons and opportunities for the charcoal (and biochar) industries. It adds two additional revenue streams, which have not been fully explored in the past.

First, the introduction of cogeneration reduces greenhouse gas (GHG) emissions. This opens opportunities to sell this environmental service in carbon markets. Pyrolysis intentionally promotes incomplete combustion, and many gaseous compounds present in the pyrolysis products are potent GHGs including methane, which has a global warming potential that is 25 times higher than CO_2 (IPCC, 2007).

Studies have measured methane emissions from charcoal production ranging from 22 to 89 kg of methane per ton of charcoal (Bailis, 2009; Taccini, 2010). In addition, although it is not traded in carbon markets, carbon monoxide, which is emitted in large quantities, also carries a global warming impact greater than CO_2 (IPCC, 2007). Burning the pyrolysis gas for cogeneration can reduce emissions of CO and CH_4 by over 90% (Cardoso, 2010). The CH_4 fraction of these reductions can be sold in the carbon market.

The co-generation of low carbon electricity would produce additional carbon credits if the power generated displace (avoid or substitute) generation systems based on fossil fuels (Bailis et al., 2013-this issue). Indeed, a Life Cycle Assessment (LCA) of the charcoal production in Brazilian conditions with cogeneration, finds that that charcoal produced in metal container kilns with additional cogeneration capability (as described above in Fig. 2) could reduce the carbon footprint of conventional charcoal production (without cogeneration) over 50%.[4]

In addition to carbon credits, the conversion of pyrolysis gas to electricity creates a revenue stream from the electricity itself. The power produced from burning pyrolysis gases could be for self-consumption by the charcoal producer, although it will likely exceeds the power required to run the facility. Alternatively, the power can be sold to third

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[4] See Bailis et al. (2013-this issue) in this issue for a full description of the assumptions and sensitivities underlying this result.

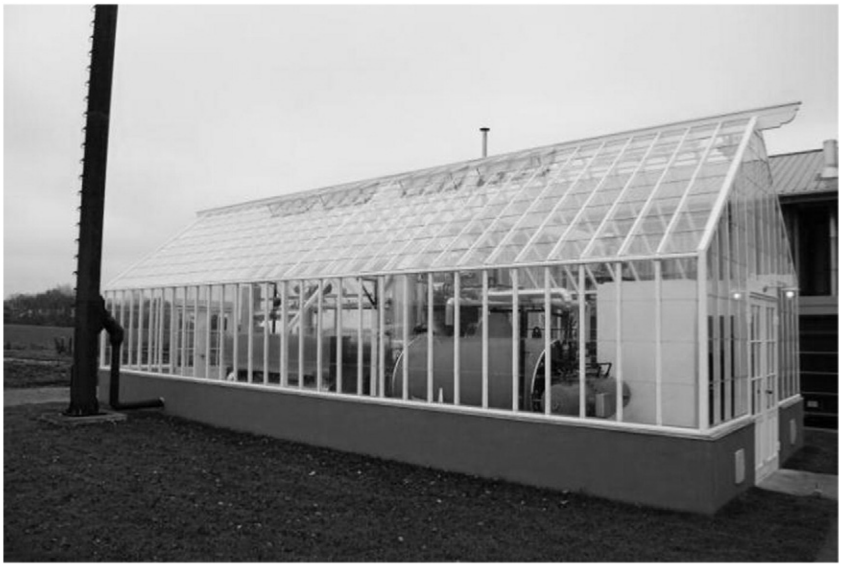

Fig. 5. Biochar plant in Denmark, with 35 KWe cogeneration capacity, powered by Stirling engine.

party users or used for distribution to the public either through the national power grid or through isolated power grids.

The potential electric power output from pyrolysis gases is 500–600 kWh of power per ton of charcoal produced (Bailis et al., 2013-this issue; Miranda, 2012). The exact value depends on efficiency of pyrolysis itself, as well as the equipment used to produce electricity. In Brazil, which produces 6–9 million tons of charcoal per year (EPE, 2011), there is a potential to cogenerate 3–5 TWh of power yearly. Nevertheless in practical terms only half of that capacity could be implemented in the near future, since half of the charcoal production in Brazil is in the hands of small producers, where likely such technology investment would not be feasible under current business practices.

Although at much smaller scale, power cogeneration from charcoaling could likely follow the footsteps of the sugar cane industry, where bagasse has now become an import fuel for power cogeneration, and bring additional significant revenues to the business. Nowadays nearly all new sugar-cane crushing plants being constructed for sugar or ethanol production consider sale of electricity as one of its co-products (BNDES, 2008).

Technology considerations

To select the equipment that will transform the fuel into energy, we need to consider the quality of the fuel being used. Pyrolysis gases consist of CO, CO_2, H_2, CH_4, water, condensable liquids, and tar. The presence of water reduces the energy content while the tar renders the untreated gaseous mixture unsuitable for sensitive equipment such as internal combustion (IC) engines and gas turbines. This leaves several options. First, the hot gases may be sent directly to a boiler where they are readily combusted. This is most easily coupled with a steam turbine. Indeed, the steam-cycle is the most reliable and affordable equipment for the range of 100 kW to 5 MW, the likely range for charcoal cogeneration. This is currently being implemented at a pilot-scale facility in SE Brazil (see Bailis et al., 2013-this issue for additional details).

A second possibility is to clean or convert the tar in pyrolysis gas so that the gaseous mixture is suitable for use in an IC engine. Pacific Pyrolysis (an Australian company) has developed a process to produce syngas by cracking of the tar. This is a process in which complex organic molecules are broken down into simpler molecules such as light hydrocarbons. This company is offering charcoal and biochar[5] production plants with cogeneration capabilities that use syngas to produce electricity in IC engines.

Other possibilities exist including equipment that accommodates external combustion chambers such as Stirling engines, which are appropriate for smaller capacities (<150 kW), and External Combustion Gas Turbines (ECGT). The Danish company Stirling DK has built a 35 kW_e biochar cogeneration plant using a Stirling engine that burns the pyrolysis gases and uses the heat to produce electric power (Fig. 5). Similarly, Btola, an Australian company, is developing a new generation of ECGT system that is expected to be more cost-effective and efficient means of transforming low quality fuels into electric power (Btola, 2011).

Charcoal cogeneration and Africa

The emergence of charcoal cogeneration technology has particular significance for sub-Saharan Africa. The region is the largest producer and consumer of charcoal in the world with about 29 million tons produced in 2011 (FAO, 2011). Projections for 2030, indicate that this demand may well double (Bailis et al., 2005). At the same time, while the number of people lacking access to electricity throughout most of the developing world is forecast to decline in the coming decades, the IEA (2011) expects sub-Saharan Africa to be the only region in the world where the number of people lacking access will increase (from 585 million in 2009, to 645 million in 2030). The bulk of people lacking access will reside in rural areas, where charcoal will continue to be produced.

Currently, the unused pyrolysis gases emitted to the atmosphere from charcoal kilns around the region could provide as much as 13.4 TWh of power with the technologies discussed previously. This represents a hypothetical installed capacity of 1680 MW (Miranda, 2012). If a small portion of this potential were utilized for charcoal cogeneration, there could be hundreds of small power plants throughout Africa, generating electricity for local villages and small business, or earning revenue through sales to the national grid.

Estimations of the business potential for charcoal cogeneration in Africa by Miranda (2012) indicate that a charcoal cogeneration plant could at least triple revenues relative to sales of charcoal made with traditional earthen kilns used throughout sub-Saharan Africa today. This would arise through a combination of changes including a doubling of efficiency in wood-to-charcoal conversion, electricity sales, plus revenues from carbon credits discussed above.

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[5] Biochar is charcoal used for soil amendment.

Cogeneration could be a very important add-on to charcoal production in sub-Saharan Africa. Not only could provide electricity to a region in desperate need for it, but it could also generate sufficient revenues to attract investment into charcoal production along with the political will required to formalize the industry. Together, both capital and political will could foster investment in sustainable forestry, and overcome one of the main criticisms of the charcoal industry in Africa today, which is the complete lack of sustainable firewood supply.

However, to develop the cogeneration potential in Africa, a new business model would be necessary. Within the current context of very small, dispersed and itinerant charcoal producers, lacking the ability to invest in technological advances or basic forest management, cogeneration would not work. This is no different than half of Brazil's charcoal industry. To introduce cogeneration in sub-Saharan Africa's charcoal sector, a new generation of charcoal producers would be necessary, with professional business management, investments in technology with larger more centralized production in order to generate enough gas for cogeneration. In addition, it would require significant investment in sustainable forestry.

As the technology develops and become mature, complementary research is needed to adopt it to African conditions, and feasibility studies would be needed for specific countries. The legal framework to produce and sell both charcoal and electricity must be considered, and, if feasibility studies are favorable, the business models to operate this new industry in appropriate countries should be developed.

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